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Experiments on the positive column in a longitudinal magnetic field

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With 6 figures in the text

ABSTRACT

The abnormal diffusion of the positive column in a longitudinal magnetic field observed by Lehnert has been investigated with a new apparatus and with improved techniques. The measurements confirm earlier results and extend these to a wider range of pressures, discharge currents, magnetic fields, and to different gases. The experimental method has been checked by a number of tests. The noise in the discharge current and the ion current to electric probes inserted in the plasma indicate a transition of the state of the discharge and an enhancement of the diffusion rate. This occurs near the critical magnetic field observed in earlier measurements on the potential gradient. Some features of the abnormal diffusion phenomenon are discussed on the basis of observations.

I. Introduction

Recently the validity of the classical theory of diffusion of charged particles across a magnetic field has been extensively discussed (Bohm 1949, Bohm *et al.* 1949, Bostick and Levine 1955, Simon 1955, 1958, and Bickerton and von Engel 1956). To re-examine the subject, Lehnert (1958) carried out an interesting experiment by using a very long discharge tube inserted in a longitudinal magnetic field. A helium discharge was run in the tube and the potential gradient was measured as a function of the magnetic field. On the basis of the classical diffusion theory and the energy balance condition for a positive column, the rate of the radial diffusion was expressed in terms of the measured potential gradient. The experiment showed that the rate of diffusion decreased with increasing magnetic field in agreement with the classical theory only up to a certain critical field strength B_c, beyond which abnormally large radial diffusion was observed.

This phenomenon has been studied in detail with a new apparatus and improved techniques. The abnormal diffusion phenomenon was found to exist in different gases and was independent of minor imperfections of the experiment such as small inhomogeneities in the magnetic field and impurities in the gas. Parts of the results obtained will be given in connection with the theory and discussions elsewhere (Hoh and Lehnert 1960). The abnormal diffusion phenomenon has also been observed in other experimental arrangements (Bostick and Levine 1955, Zahrinov 1960, and Allen *et al.* 1959).

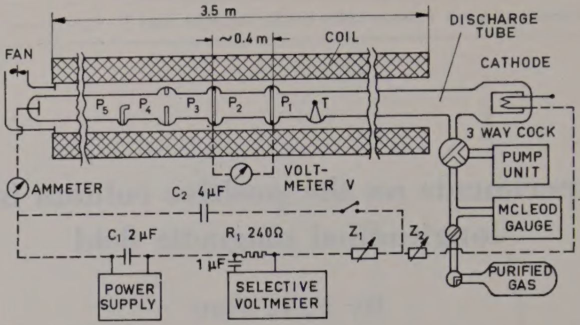


Fig. 1. Experimental arrangement. The electrical circuit is drawn with dashed lines. Usually Z_1 and Z_2 are resistances of some kΩ. P_1 to P_5 are electrostatic probes and T is a thermo-couple.

The existence and the behavior of the critical magnetic field B_c may be explained by an instability of the wall sheath (Hoh 1960). An alternative theory has also recently been given by Kadomtsev and Nedospasov (1960).

II. Experimental arrangements and methods

Fig. 1 shows the experimental apparatus. Discharge currents I from 0.01 to 1 A were run through the discharge tube. Helium, argon, krypton, hydrogen and nitrogen were used at pressures p_0 (normalized to 0°C) between 0.1 and 4 mm Hg. The potential gradient, the probe current and the noise in the discharge current were recorded as a function of the magnetic field B up to 0.9 Vs/m^2.

(a) *The magnetic field*

The magnetic field consisted of 7 coils, each 0.5 m long. The coils were wound with glass-fibre-insulated copper wire (6 × 4 mm^2) upon a 60-mm brass tube with the windings separated by 1-mm spacing in all directions, and were baked and impregnated with insulating lacquer. This procedure enabled continuous cooling of the coils in a water bath and prevented electrochemical reactions between the water and the copper. Currents up to 900 A, corresponding to a magnetic field of 1 Vs/m^2 and a power input of 1 MW were used. At the highest current applied, the water boiled within some seconds, which time was just sufficient for a measurement. The reduction of the field at the coil junctions was about 5 % of the mean value. The influence of these junctions was also checked by measurements made in a 4-meter-long homogeneous coil of similar construction yielding 0.3 Vs/m^2.

(b) *The discharge tube*

Three tubes with inner radii r of 1.0, 0.76 and 0.535 cm were used. Each tube was made of Pyrex glass and was free from surfaces contaminated with grease, except the 3-way cock which connected the tube to the external system (Fig. 1). In order to eliminate the end effects described by Simon (1955, 1958), the tubes were made 4.1 m long and ended outside the magnetic field. Some measurements were also carried out in a 2.4-meter-long tube with a radius of 1 cm. A hollow cathode, made of a nickel

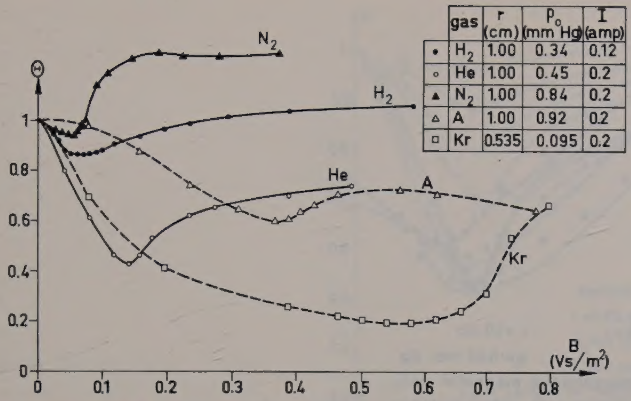


Fig. 2. The normalized potential gradient, $\Theta = E(B \neq 0)/E(B=0)$, of the positive column in different gases as a function of the magnetic field.

cylinder with a tungsten wire inside, was used. The potential gradient was measured between the probes P_1 and P_2 (Fig. 1) which consisted of 0.3-mm-thick platinum wires attached to the wall. The probes P_3, P_4 and P_5 were made of 1-mm-thick tungsten thread coated with glass and cut flush at their end surfaces. A thermocouple T measured the gas temperature. The tube was cooled by a fan.

(c) *Outgassing procedure*

Before the measurements, the tube was baked by running it with strong currents using He gas. Impurities from the wall and the electrodes were released in the presence of high temperature and the gas was then promptly pumped out. The system was "rinsed" in this way by being pumped and refilled many times, first with He (to produce a high temperature of about 350°C) and then with the desired gas.

The gases were obtained from the Norwegian Hydroelectric Company in sealed bottles. He and Kr were spectroscopically pure, A and N_2 chemically pure and the H_2 gas was purified by a palladium filter. After the pressure was registered, the tube was closed by the 3-way cock (see Fig. 2). As shown by the pressure gauge, the gas density was found to be constant during the discharge. A small hand spectroscope indicated that the discharge could be kept clean for more than a day. The cleanness was further enhanced through cataphoretic drift of impurities into the cathode region (Loeb 1958).

A carbon trap cooled with liquid air was inserted in the tube system. However, this was found to be of no advantage; on the contrary, the pressure varied both when the trap absorbed and released gases. At pressures lower than 0.4 mm Hg, the cathode sputtering became strong. The pressure decreased during the discharge on account of the trapping of gas molecules between the wall and the deposited material in the cathode region (see Flügge 1956).

III. Potential gradient measurements

The voltage drop across P_1 and P_2, giving the potential gradient E, was measured with an electrostatic voltmeter except in a few cases where a voltmeter of very high

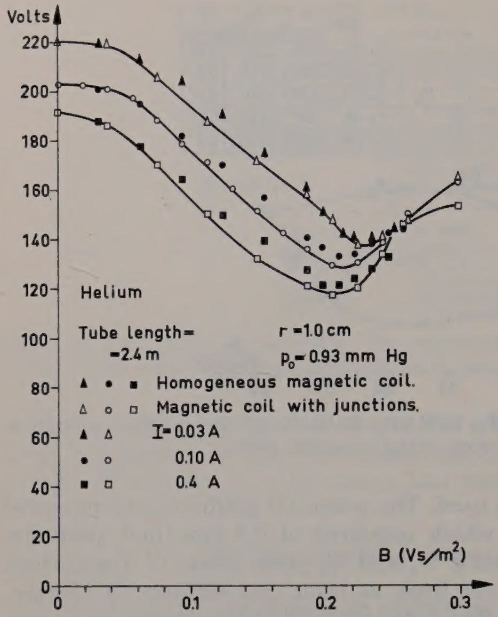


Fig. 3. Potential gradient across a He positive column as a function of the magnetic field. The full marks were measured in a homogeneous magnetic field. The probes were 0.436 m apart.

impedance was used. Some curves describing the variation of the normalized potential gradient $\Theta = E(B \neq 0)/E(B = 0)$ with the magnetic field B, are shown in Fig. 2. A sudden increase or "dip" in the $\Theta - B$ characteristics occurred at a critical magnetic field $B = B_c$ and this was accompanied by an increased noise level in the current to all electrodes of the tube. Most measurements were made in He.

In rare gas discharges, an insertion of small amounts of impurities (H_2O, N_2, O_2) made the E values higher. The "dip" persisted, but was displaced towards lower magnetic fields. When the neutral gas temperature (50–300°C) increased, it was found that E was decreased by a small percentage, whereas the position of the "dip" remained constant. Possible sources of experimental error may be traced to the neutral gas temperature variations and to uncertainties in the pressure measurements.

Compared with the measurements made by Klarfeld (see Flügge 1956), the present potential gradient values in the absence of magnetic fields are slightly lower for He, Ar and Kr at $I = 0.3$ A and $r = 1$ cm. The potential gradient for H_2 in the absence of magnetic fields agrees with the empirical formula given by Gütherschultze (see Flügge 1956) within an error of 10%. For N_2 the corresponding gradient decreased appreciably with increasing temperature. As the tube was rapidly heated in the N_2 discharges, only the relative values Θ at each instant are given. Very pronounced standing striations in the H_2 discharges were observed. These, however, disappeared at a magnetic field of some hundred gauss.

The probes P_1 and P_2 were usually centered in the middle section of the magnetic coil. The influence of the coil junctions was studied by displacing these probes to include a coil junction. However, this arrangement did not result in any measurable change in the $\Theta - B$ curves in helium. The influence of the coil junctions was further studied by inserting the discharge tube in a homogeneous coil, yielding a maximum field of 0.3 Vs/m². Fig. 3 shows that the $\Theta - B$ curves measured under similar condi-

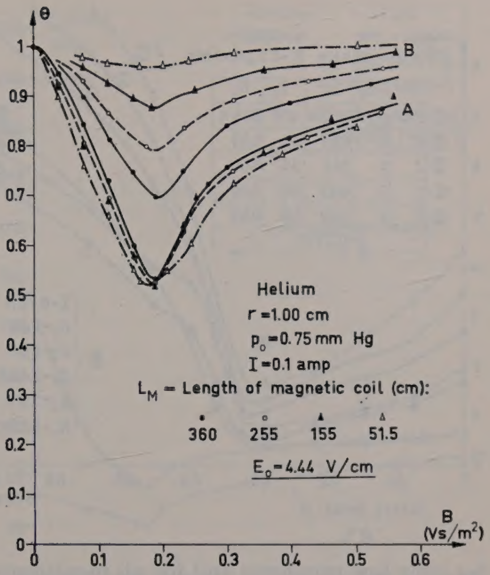


Fig. 4. Potential gradient of a He positive column, A, and the fractional voltage drop between anode and cathode, B, as a function of the magnetic field B and the length of the magnetic coil L_M. The probes P_1 and P_2 were centered in the mid-coil.

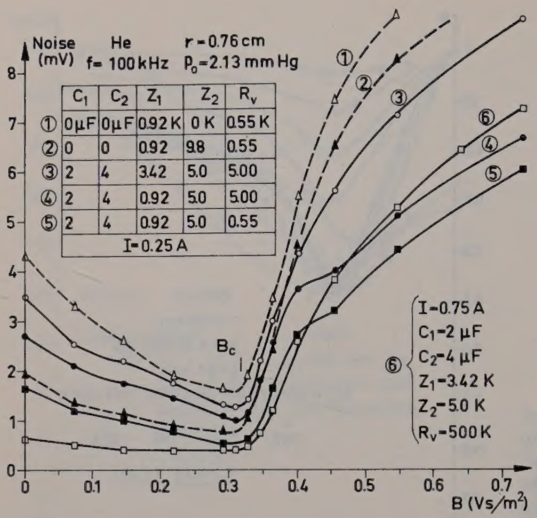
tions in both kinds of magnetic fields follow each other very well. The slight difference may result from the fact that the magnetic field near P_1 and P_2 was somewhat larger than the average field strength.

In some He discharges with $r = 1$ cm, a condenser bank of 8000 μF was connected across the magnetic field coil to short-circuit the noise in the magnetizing current. Further, the tube was inclined about 1 degree to the field direction. In both cases, no noticeable change was observed. Thus, it can be concluded that the small imperfections of the magnetic field had no influence upon the characteristics of the discharge. This is also expected, as the mean free path and collision time in the present pressure range are much smaller than the curvature and the time scale of the magnetic field.

The length of the magnetic coil L_M could be varied by disconnecting the coil sections. When this was done, the position of the "dip" point was not influenced in He discharges for all cases investigated (Fig. 4). However, the "dip" point in A and Kr disappeared or at least was displaced to a much higher magnetic field, when L_M was made smaller than 50 to 100 tube radii. Finally, a reduction of the tube length from 4.1 to 2.4 m at $r = 1$ cm, did not influence the results, neither when the anode was placed outside the magnetic field nor when it was inside.

The power supply had a 300-Hz current pulsation of about 4 % together with some audio-frequency noise. These disturbances were usually damped by a low pass filter (C_1, Z_1 and C_2 in Fig. 2). Inductances of some henries and resistances from 0.2 to 12 kΩ were inserted in series with the tubes (Z_1 and Z_2 in Fig. 2). Measurements of this kind in He showed that within the limits of experimental error, neither the disturbances from the current source nor the external impedance influenced the observed potential gradients.

Generally, the critical field B_c increased with increasing gas pressure and decreasing tube radius. For $B > B_c$, the values generally increased monotonically with B. Only



	C_1	C_2	Z_1	Z_2	R_v
①	0µF	0µF	0.92 K	0 K	0.55 K
②	0	0	0.92	9.8	0.55
③	2	4	3.42	5.0	5.00
④	2	4	0.92	5.0	5.00
⑤	2	4	0.92	5.0	0.55
	I=0.25 A				

Fig. 5. Noise in the cathode current as a function of magnetic field at 100 kHz and 5 kHz bandwidth. R_v is the internal resistance of the selective voltmeter. Other notations can be found in Fig. 1.

for very low pressures and for all measurements with A and Kr this was found not to be the case (Fig. 2). For these gases the $\Theta - B$ curves usually showed both a maximum and a minimum in the range $B > B_c$. It was also found that the "dip" position as well as the form of the $\Theta - B$ curve depended upon the pressure, the tube radius, the gas and slightly upon the current. More detailed results have been given together with theoretical calculations elsewhere (Hoh and Lehnert 1960).

IV. Noise and probe measurements

The noise in the cathode current was measured across a resistor in the discharge circuit by means of a selective voltmeter (Fig. 1). Generally, it was found that the noise versus the magnetic field curve in He exhibited a similar "dip" at $B = B_c$ at frequencies lower than about 100 kHz. The increase in the noise level at frequencies higher than 100 kHz occurred at a magnetic field somewhat stronger than B_c.

The dependence of the noise on the external impedances and the discharge currents is illustrated in Fig. 5. Since the cathode and anode regions were not influenced by the magnetic field and since the noise from the power supply was short-circuited by the condensers, the noise observed was associated mainly with the positive column. A comparison between curves 3 and 6 in Fig. 5 shows that the noise depended strongly on the current for $B < B_c$. However, when $B > B_c$, the noise level was found to become a weak function of the current. In other words, the oscillations generated in the positive column are not sensitive to the plasma density. An analysis of Fig. 5 further suggests that the plasma noise generation was associated with an equivalent impedance which was strongly non-linear.

In He discharges at higher pressures (2–4 mm Hg) no resonance peaks were found in the noise spectrum. However, at a lower pressure, $p_0 = 0.53$ mm Hg, $r = 0.76$ cm, $I = 0.1$ A and with external impedances shown in curve 3, Fig. 5, the noise spectrum showed sharp resonance peaks at multiples of 22.2 kHz in the absence of the magnetic field. These peaks broadened out rapidly when $B > B_c$. It was also observed that the

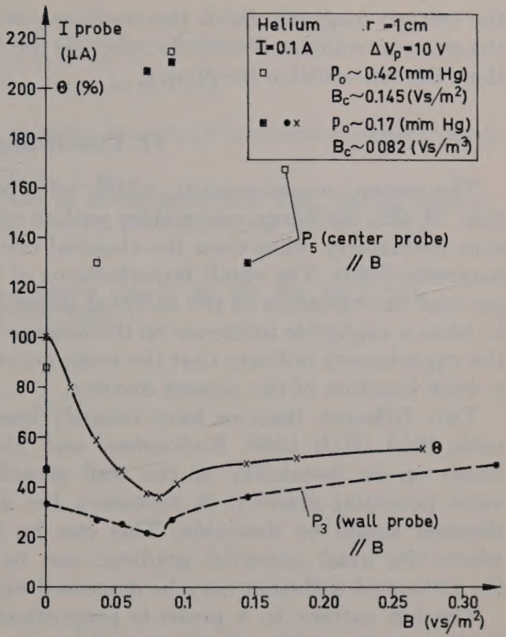


Fig. 6. Ion current to the probes versus the magnetic field. The probes were biased to -10 V with respect to the currentless probe potential. For comparison, the normalized potential gradient Θ has also been shown in the same diagram.

frequencies of these peaks increased only by some kHz when C_2 was reduced to half its value. The existence of this effect depended very much on the values of the external impedances, the discharge current and the gas pressure. It is possible that this phenomenon was associated with the moving striations. Finally, the noise characteristics measured at the probes P_1 and P_2 were of similar type as those obtained for the noise in the discharge current (Fig. 5).

For He at lower pressures ($p_0 \approx 0.5$ mm Hg) and with $r = 1$ cm, the ion currents to the probes P_3, P_4 and P_5 were measured by biasing the probes down to -60 volts with respect to the potential of an isolated probe. The ion current to the wall probe P_3 versus the magnetic field showed a similar "dip" and the ion currents to the center probes P_4 and P_5 first increased with the magnetic field and later decreased when $B > B_c$ (Fig. 6).

The light intensity from the plasma is proportional to the electron density and is a very sensitive function of the electron temperature. By keeping the electron density constant, which corresponds to a constant $p_0 I/E$ value (Lehnert 1958) the light intensity was found to increase as the magnetic field passes its critical value B_c. It is therefore likely that the abnormal diffusion phenomenon is associated with an enhanced electron temperature.

V. Discharge conditions

The conditions of Schottky's theory for the positive column are satisfied in this experiment. The degree of ionization ranged from 10^{-4} to 10^{-8}, the electron temperature was about 15,000–40,000°K and the ion temperature about 300–1000°K. Near the critical magnetic field, the electron-gyration frequency was about 5–100 times the electron-collision frequency, whereas the ion-gyration frequency was much smaller than the ion-collision frequency.

VI. Concluding remarks

The present measurements, which were performed in different gases under variation of the discharge parameters within wide limits, strongly suggest that a diffusion mechanism other than the classical one is operative in gas discharges in strong magnetic fields. The small imperfections of the magnetic field, the impurities of the gas and the variation of the external impedances in the discharge circuit were found to have a negligible influence on the measurements of the potential gradient. Further, the experiments indicate that the noise generated in the abnormal diffusion region is a weak function of the plasma density.

Two different theories have recently been advanced to explain the critical magnetic field (Hoh 1960, Kadomtsev and Nedospasov 1960). The former theory is based on an instability of the wall sheath. In the latter one a sufficiently large axial potential gradient is necessary for instability. A distinction between these theories would be desirable. This can be made e.g. by performing an experiment where the axial potential gradient can be removed. In any case some features of the enhanced diffusion may be discussed on basis of the experiment.

The ion current to a probe is proportional to the plasma density (Bohm 1949). As long as the radius of gyration of ions is larger than the mean free path and the sheath thickness, the ion currents to the probe can be shown to be independent of the magnetic field. Hence the probe current can be taken as a measure of the plasma density near the probes. In Fig. 6 it is seen that the ion current to the wall probe P_3 first decreases with increasing magnetic field. As the magnetic field passes the critical value B_c, the ion current starts to increase. The ion currents to the center probe P_5 show a similar change at B_c but in a reversed direction (Fig. 6). From this it may be concluded that the radial density distribution is flattened out and an enhanced density gradient is set up near the wall when $B \geqslant B_c$. This result has also been found by Allen *et al.* (1959) in a different way. Whatever the diffusion mechanism in the center part of the plasma may be, the high density gradient near the wall should enable the plasma to be "drained off" effectively in combination with oscillations. These have also been observed in the form of an increased noise level. The increased particle loss must be compensated by an enhanced rate of production, which is equivalent to an enhanced electron temperature. This reflects itself in an increase in the potential gradient, in the power input and in the light intensity.

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